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RESIDENTIAL SPACE HEATING SYSTEMS: ENERGY CONSERVATION AND ECONOMICS[*]

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ABSTRACT

Annual energy use for residential space heating was 8.6 Quads in 1975. This accounted for over 50% of the energy used in the residential sector and 12% of energy used in the U. S. that year. Because residential space heating accounts for such a large share of energy use, improvements in new space heating systems could have significant long-term conservation effects.

Several energy-saving design changes in residential space heating systems are examined to determine their energy conservation potential and cost effectiveness. Both changes in conventional and advanced systems are considered. Conventional design changes include options such as the flue damper, sealed combustion, electric ignition and improved heat exchangers. Some of the advanced designs include the gas heat pump, pulse combustion furnace, and dual speed compressor heat pump. The energy use and cost estimates are developed from current literature, heating and equipment manufacturers and dealers, and discussions with individuals doing research and testing on residential space heating equipment.

Results indicate that implementation of conventional design changes can reduce energy use of representative gas, oil, and electric space heating systems by 26, 20, and 57%, respectively. These changes increase the capital cost of the systems by 27, 16, and 26%. Avanced gas and electric space heating systems can reduce energy use 45 and 67% respectively. However, the advanced systems cost 80 and 35% more than representative gas and electric systems.

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INTRODUCTION

From 1960 to 1975, energy use for residential space heating grew from 5.1 EJ[**] to 9.1 EJ (1,2). The energy used for space heating accounted for over half the total energy used in the residential sector during this time. Because space heating accounts for such a large share of residential energy use, improvements in new space heating systems could have significant long-term energy conservation effects.

The HVAC (Heating, Ventilating and Air-Conditioning) industry is currently developing and marketing more efficient gas, oil, and electric space heating systems that use less energy than systems currently in use. Some of the new systems incorporate conventional design changes (such as the flue damper or electric ignition for gas furnaces), while others are advanced technology systems (such as the gas heat pump and the ACES [Annual Cycle Energy System]). This paper examines the energy saving and increased capital cost expected with these more efficient systems (both conventional and advanced) compared to representative systems currently in use (3).

The potential impact these more efficient systems might have in reducing growth of residential energy use is also examined. The energy and cost estimates are used as inputs to the Oak Ridge National Laboratory (ORNL) engineering-economic model of residential energy use (4). Estimates of the savings in residential energy use to the year 2000 are provided by the model.

MARKET TRENDS

Table 1 shows a breakdown of the eight most common heating systems in existing single-family residences for the years 1970, 1973, 1974, and 1975 (5). For both gas and oil, the central forced-air system was the most common system for each of the four years. The forced-air central furnace was chosen as the representative system for analysis of gas and oil heating.

Built-in electric systems (which include baseboard and ceiling cable) were the most common electric systems in existing homes from 1970 to 1975. However, the number of homes heated with central electric funaces increased by 255% during this time compared to 50% for built-in electric systems. In 1975, electric furnaces accounted for 52% of new electrically heated residences compared to 26% for built-in systems (6,7.8). Because of its rapid growth and large share of the electric heating market in recent years, the central forced-air funace was chosen as the representative electric heating system.

GAS SYSTEMS

The annual energy requirements and capital costs of several advanced gas heating systems and energy conserving design options for a representative gas furnace are examined in this section. The energy usage data were developed from recent literature, (9-14) while cost data were obtained from manufacturers and dealers of gas heating equipment and available literature (9,14). Complete details are given in ref. 3.

The reported energy saving (and capital cost) of each of the energy conserving design options varied widely in the above references. (See Ref. 3 for a full list of reported ranges in energy savings and capital cost increases for the design options.)

The base house used in this analysis is located in Philadelphia. It has a design heating load of 43 MJ/hr and an annual heating load of 52.3 GJ. The base furnace is an atmospheric unit, located within the conditioned space and double oversized.[*] Reference 15 suggests that double oversizing of residential gas furnaces is "typical" practice. Characteristics of the reference gas heating system are listed in Table 2.

Seasonal performance factors (SPF) from available literature are averaged to determine the SPF and annual energy consumption for particular energy conservation design options. (See Appendix for SPFs and details on calculations. For a heating system, the SPF is efined as:

$$\text{SPF} = \frac{\text{Annual heat energy provided by the system}}{\text{Annual fuel energy used by the system}}$$

Total energy used by the system includes the fuel used for heating plus auxiliary energy such as electricity used for air distribution.

Energy savings and installed cost increases are evaluated for several energy saving design modifications to the base furnace (see Fig. 1). These include:

Properly sizing the unit - With the reference furnace properly sized, the calculated annual energy saving is 4.2 GJ (10.12). For a natural gas price of $1.78 per GJ (the 1975 national average price), the annual saving is $6.70. The saving in capital cost with the properly sized unit is $150.

Adjusting the bonnet thermostat to 2.8°C above room temperature - Gas furnaces have a

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[*] A heating system is properly sized when its output matches the design heating load of the house. A double oversized system has a rate output twice the design heating load of the house.

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[**] 1 EJ = 10^{18} J.

thermostat that senses the bonnet air temperature and controls when the circulating air fan comes on and off. Typically, the fan is set to come on between 52 and 60°C and turn off at 38°C (10). Adjusting the thermostat so the fan comes on and off at 2.8°C above room temperature reduces annual energy use by 5.5 GJ, decreases fuel cost by $9, and incurs no increase in capital cost (10,12,14).

Installing an automatic flue damper - During the off cycle, heat escapes up the flue of the standard atmospheric combustion furnace. An automatic flue damper closes the flue during the off cycle to prevent heat from escaping. Adding a flue damper to a furnace increases the installed cost $85. The calculated annual energy reduction is 10.3 GJ; this yields an annual saving in fuel cost of $17 and a payback period of 5 years (11,12,14).

Installing 5.1 cm of fiberglass duct insulation instead of 2.5 cm - Installing 5.1 cm of insulation adds $20 to the capital cost, decreases annual energy use 2.2 GJ and saves $3.50 in fuel costs. The payback period is 5 years.

Switching to a sealed combustion unit - A sealed combustion furnace has its combustion chamber separated from the conditioned air in the house. Its combustion air is drawn directly from the outside and, in many cases, is preheated by the hot combustion products in the flue. A sealed combustion unit costs about $140 more than a comparable atmospheric combustion unit. The annual fuel and cost savings are 11.5 GJ and $18, respectively (10, 11,12,14).

Increasing the steady state efficiency to 84% - The theoretical upper limit of the steady state efficiency before water starts to condense on the heat exchanger or flue is about 84% (12).

To approach this limit, several furnace modifications must be made: redesigning the heat exchanger, constructing the heat exchanger from rust resistant materials such as aluminized steel, and adding an induced draft fan (12,14). The cost of the unit increases $115. The calculated annual energy and cost savings are 14.7 GJ and $24, respectively. The payback period is 5 years.

Installing electric ignition - The pilot light in the base furnace operates continuously. When the circulating fan (blower) is not in operation, the pilot heat is not delivered to the living area. The calculated energy loss is 4.2 GJ/yr (10,11,12,14). With electric ignition, this loss is eliminated. This adds $90 to the cost of the furnace and reduces annual fuel costs $6.70. The payback period is 13 years.

Advanced gas heating systems - There are several advanced gas heating systems being developed for residential applications. These include organic fluid absorption heat pumps, Stirling/Rankine heat pumps, and pulse combustion furnaces. References 9, 14, and 16 give descriptions of these systems.

The projected heating SPFs for the three systems are given in Table 3 (9).

Only price estimates for the organic fluid absorption heat pump were available. The heat pump[*] used with the base house has an estimated installed cost of $3540 (9).

OIL SYSTEMS

The energy use estimates for the oil furnace are developed from refs. 9, 12, 14, 15, and 17. Cost data are obtained from manufacturers and dealers of oil heating equipment. The same house and weather conditions used for the gas furnace are also used for the oil furnace analysis. The furnace is located within the conditioned space and double oversized. The characteristics of the base oil heating system are listed in Table 4.

Energy savings and installed cost increases are evaluated for the same design options listed for the gas furnace with the exception of electric ignition. Oil furnaces already come equipped with electric ignitors.

The effect of design changes to the base furnace is shown in Fig. 5. The energy conservation potential for the oil furnace is smaller than the gas furnace. The energy use of the furnace can be decreased 20% for an added capital cost of $290, with a payback period of 7 years.

ELECTRICAL SYSTEMS

The energy use and cost data for electrical heating systems are developed from refs. 9 and 18. The base house used for gas and oil systems is also used to evaluate the effects of conservation options for electrical heating systems. However, the house is placed in two cities - Cleveland and Atlanta. The two cities are used to provide sufficient climatic variation to evaluate annual heat pump performance, which is very climate dependent. The characteristics of the base house for the two cities are listed in Table 5 (9). A cental, forced-air electric furnace was used as the reference heating system. The base furnace in the Cleveland house is rated at 55.4 MJ/hr,[+] while the one in the Atlanta house is rated at 38.2 MJ/hr (9).

The installed costs of the central electric furnaces (plus air conditioning) are $2800 and $2490 for Cleveland and Atlanta, respectively (9). The ductwork and duct insulation, and their associated prices are the same as those used previously. The electricity price is $0.032 per kWhr (1975 national average).

Conventional heat pumps use less energy than the base heating system. Even a representative 1975 heat pump with a coefficient of performance

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[*] Because the gas heat pump provides both cooling and heating, while gas furnaces provided only heating, the price of the heat pump was adjusted to account for its cooling capabilities. The price of a central air conditioning system ($1200) was subtracted from the price of the organic fluid absorption heat pump. This yielded a price of $2340 for the heat pump for comparison with the furnaces.

[+] All electrical energy figures in this section are end use energy.

(COP)[*] of 1.6 at -8°C and 2.6 at 8°C ambient temperature has a seasonal performance factor of 1.68 and 1.97 in Cleveland and Atlanta, respectively (9). For Cleveland, this yields reduction of $250 in annual fuel bills over the central electric furnace. For Atlanta, a $130 reduction is calculated. The payback period is one year in Cleveland and two years in Atlanta.

The energy conserving options are from refs. 9 and 18. The options from ref. 9 are heat pump designs already on the market (labeled as "high efficiency" heat pumps).[**]

Various optimized heat pump designs are considered in ref. 18 using a heat pump computer simulation program. The primary changes in component design deal with the compressor: placing the compressor indoors, using a two speed compressor motor, and using two equally sized compressors. The heat pump systems are optimized for these three design changes at different design (or balance) temperatures.[†] Other design changes in the optimization included: indoor and outdoor coil effective size and air flow rates, fin spacing, number of rows of tubes, fraction of indoor coil devoted to liquid subcooling, and indoor duct system effective size.

By placing the heat pump compressor indoors, heat loss from the compressor shell is utilized inside the house. This modification can provide a gain of up to 20 percent in capacity and COP (18). Using either a two speed compressor motor or two equally-sized compressors allows the heat pump to better match the heating load, thus reducing the on-off cycling at lower heating loads and saving energy.

The annual energy use and capital cost of the energy conservation design options for electric heating systems are shown in Figs. 3 and 4 for Cleveland and Atlanta, respectively. Even though the percentage energy saved for a particular option is larger in Atlanta than Cleveland, the energy saved is larger in Cleveland because of[‡] the larger heating load and longer heating season. The payback period for a particular design option is also shorter in Cleveland than in Atlanta.

NATIONAL IMPACTS OF IMPROVED SPACE HEATING SYSTEMS

The ORNL residential energy use simulation model (4) is used to evaluate the effects on national energy use and household economics of adopting combinations of the previously discussed space heating design options. Three cases are run with the simulation model. In the first (baseline), the market for purchasing new heating systems is allowed to operate under free market conditions and improvements in conventional systems are available during the projection period (1977-2000). The input data for this case are developed from the energy use versus capital cost curves for improvements in conventional heating systems (Figs. 1-4). For the baseline, space heating energy grows from 8.9 EJ per year in 1977 to 12.5 EJ per year in 2000, an average growth of 1.8%/year.

The second case assumes that advanced heating systems become available to consumers in 1980. These advanced systems include gas heat pumps and advanced electric heat pumps. Space heating energy use grows at an average annual rate of 1.6%. The cumulative energy use (1977-2000) is 3.9 EJ below the baseline (see Table 6). The net economic benefit is $3.4 billion.[*]

The third case is the same as the second case except it assumes consumers minimize life-cycle costs when purchasing new heating systems beginning in 1980.[**] (The previous cases assume consumers would respond to fuel and capital cost increases as they have in the past under free market conditions.) The average annual space heating energy growth rate is cut to 1.1%. The resulting economic benefit to consumers from purchasing equipment on a life cycle cost basis is $3.7 billion for the 1977-2000 period.

The ratio of economic benefits (reduced fuel bills) to economic costs (higher equipment costs) for cases 2 and 3 are 9.5 and 1.5, respectively. These results indicate that improvements in space heating performance can yield large energy and economic benefits to the nation.

CONCLUSION

A variety of technological improvements are available to reduce energy use in residential space heating systems. The energy saving possible through implementation of these improvements is surprisingly large (over 50% on some systems). At today's fuel prices, many of these design changes are cost effective with payback periods less than five years. As fuel prices increase, the economic attractiveness of these changes will increase.

The results presented suggest that these technological improvements can potentially reduce growth of residential space heating energy use to 1.0% per year compared to the historical 4% per year from 1950 to 1973.

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[*] Coefficient of performance is defined as (19):

$$\text{COP} = \frac{\text{Heat delivered by the heat pump}}{\text{Electric energy used by the heat pump}}$$

[**] Very little information was given in ref. 9 on the physical characteristics of the "high efficiency", I, II, and III heat pumps.

[†] Balance temperature is the temperature below which resistance heating is first needed to augment the heat pump.

[‡] No SPFs for the advanced systems in Atlanta were available since ref. 18 considered only heat pump performance in Northern climates (Cleveland). To estimate SPFs of the advanced systems in Atlanta, SPF improvement information was adapted from ref. 9. The average improvement in seasonal performance for the conventional heat pumps in moving from Cleveland to Atlanta was first calculated. This improvement was 18%. Each of the seasonal performance factors of the advanced heat pumps were then increased by this same amount to obtain an estimate of their SPF values in Atlanta.

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[*] Present worth at 3% real interest rate.

[**] Life-cycle cost is defined as the sum of the capital cost of the heating system plus the present worth of yearly operating costs discounted at 3%.

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Table 1. Breakdown (in percent) of eight popular heating systems in existing single-family homes

System	Year				Change from 1970 to 1975
	1970	1973	1974	1975	
Gas central forced-air	33.0	36.5	32.2	32.[illegible]	-1
Oil central forced-air	11.8	10.9	12.0	11.3	[illegible]
Oil boiler	7.7	7.9	7.5	7.4	-4
Gas floor or wall furnace	7.9	8.7	7.2	7.0	-11
Built-in electric	3.4	4.9	6.4	6.6	90
Electric central forced-air furnace	3.9	3.0	2.6	[illegible]	55
Gas boiler	5.0	3.6	3.2	4.9	[illegible]
Electric heat pump	[illegible]	[illegible]	1.2	1.3	[illegible]
Other	[illegible]	23.4	6.7	[illegible]	-12

Developed from ref. 5.

Developed from estimates given by Edison Electric Institute and ref. 5.

Table 2. Characteristics of the reference gas heating system

Furnace system	Ductwork
Location: within living area	Insulation: 2.5 cm fiberglass
Size: input - 115 MJ/hr output - 89 MJ/hr	Heat loss 3.4 GJ/yr
Type: Atmospheric combustion with standing pilot	Total cost (1975-$) - $1310
Efficiency: steady state - 77 seasonal - 61	
Annual fuel consumption: 89.6 GJ	Gas price: $1.78 per GJ

Table 3. Estimates of the SPF for three advanced gas heating systems

System	SPF[a]
Organic fluid absorption heat pump	1.10
Stirling/Rankine heat pump	1.41
Pulse combustion furnace	0.93

[a] Conventional gas furnace SPF is 0.61.

Table 4. Characteristics of the base oil heating system

Furnace system	Ductwork
Location: within living area	Insulation: 2.5cm fiberglass
Size: input - 116 MJ/hr output - 89 MJ/hr	Heat loss: 3.4 GJ/yr
Type: flame retention headburner	
Efficiency: steady state - 77% seasonal - 66%	
Annual fuel consumption: 82.8 GJ	
Total Cost of System (1975-$) - 1840	Fuel oil price: $2.95 per GJ

Table 5. Characteristics of the base house with electric heating

Item	Location	
	Cleveland	Atlanta
Living area (ft^2)	1350	1350
Design heating load (MJ/hr)	44.3	35.1
Annual heating load (GJ)	74.6	26.8

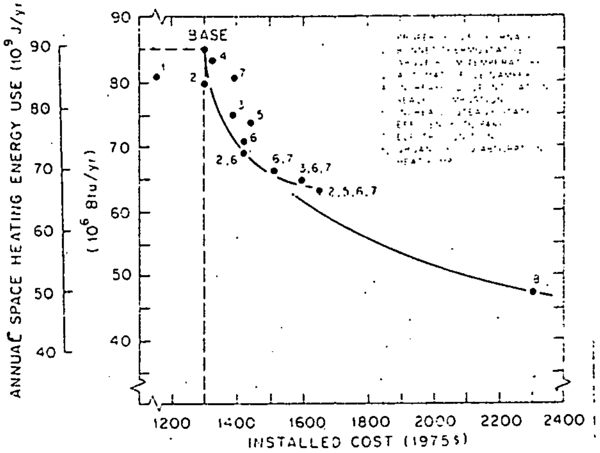

Fig. 1. Annual space heating energy use vs installed cost for design changes in a gas heating system in Philadelphia. The price of a central air conditioner was subtracted from the price of the organic fluid absorption heat pump.

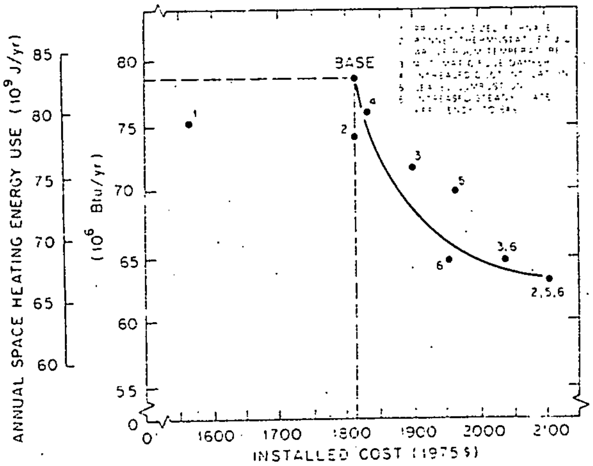

Fig. 2. Annual space heating energy use vs installed cost for design changes in an oil heating system in Philadelphia.

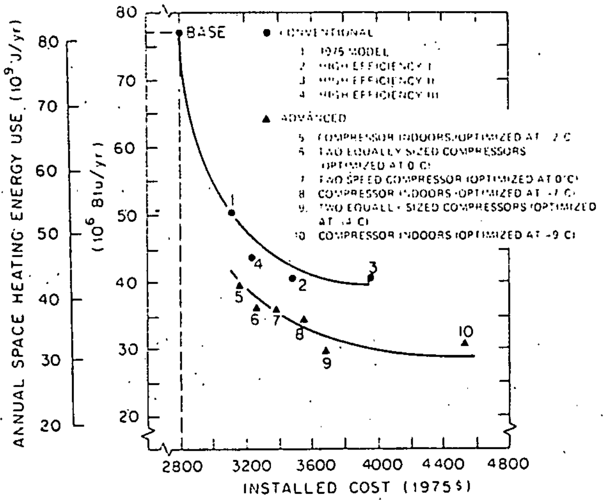

Fig. 3. Annual space heating energy use vs installed cost for design changes in an electric heating system in Cleveland. The base system included central electric furnace and air conditioner.

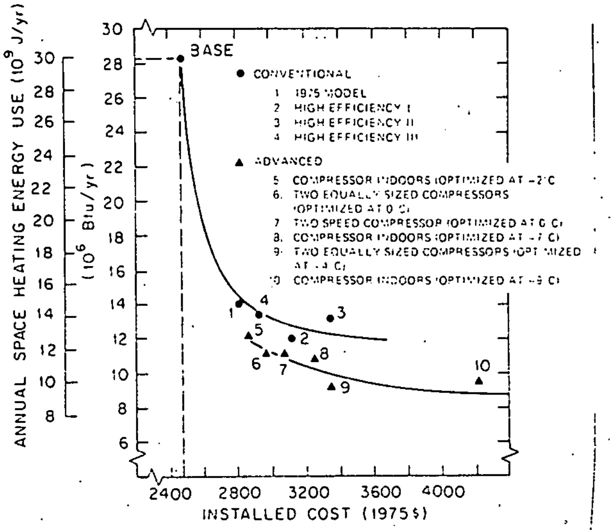

Fig. 4. Annual space heating energy use vs installed cost for design changes in an electric heating system in Atlanta. The base system included central electric furnace and air conditioner.